# Simple iodine reference at 1064 nm for absolute laser frequency determination in space applications

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Using an iodine cell with fixed gas pressure, we built a simple frequency reference at 1064 nm with 10 MHz absolute accuracy and used it to demonstrate deterministic phase locking between two single-frequency lasers. The reference was designed to be as simple as possible, and it does not use a cooler or frequency modulator. This system should be useful, especially for space interferometric missions such as the Laser Interferometer Space Antenna. © 2010 Optical Society of America

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## 1. Introduction

The Laser Interferometer Space Antenna (LISA) is a joint NASA/ESA mission for observing gravitational waves in the frequency band from 0.1 mHz to 0.1 Hz [1]. It comprises a constellation of three spacecraft forming a triangle with a $5 \times 10^6$ km arm length. Each spacecraft has an optical assembly that includes two 1064 nm single-frequency lasers and performs heterodyne interferometry between the spacecraft, achieving picometer-level displacement sensitivity. To enable precision heterodyne interferometry, all six lasers have to be phase locked with $\sim$4 MHz offset using $\sim$20 MHz bandwidth photodetectors. Because the LISA lasers may operate over a wide frequency range on the order of 30 GHz, the frequency lock acquisition of lasers on a spacecraft separated by $5 \times 10^6$ km (referred to as constellation acquisition) is a significant technical challenge. Similar frequency lock acquisition must be done between distant spacecraft in the GRACE follow-on mission for monitoring Earth gravity fields, in which two lasers for heterodyne interferometers are separated by $\sim$50 km [2]. To address this technical challenge, we present here a simple frequency reference system that monitors a small fraction of the laser power transmitted through an iodine cell. The iodine system allows absolute monitoring of the laser frequency, and thus it enables deterministic frequency locking. By using this reference on each spacecraft, it will be possible to ensure that the lasers on separate spacecraft are locked to very similar frequencies, minimizing the problem of constellation acquisition. In addition, the iodine system provides other important laser diagnostics, including monitoring of tuning efficiency and frequency drift.

A frequency reference using iodine molecules has several advantages for this task: (i) the absolute frequency of iodine lines are well known, and thus the absolute frequency of the lasers can be determined easily; (ii) the iodine vapor cell is less sensitive to temperature fluctuation and misalignments compared to other frequency references, for example, gratings and etalons; and (iii) the system can be very simple yet accurate. For example, the best commercial wavemeter, based on a He–Ne stabilized laser, can resolve 0.1 pm

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(~27 MHz) around 1 $\mu$m. However, such an instrument is too complicated for space applications and does not have enough accuracy for LISA.

In this paper we describe an iodine frequency reference with very simple setup: no frequency modulators, no temperature control for the iodine cell, and the use of a fiber-coupled frequency-doubling device. The system navigates laser frequency to one of the known absorption lines of the iodine molecule automatically. The absolute accuracy of the resultant laser frequency is better than 10 MHz, which is within the bandwidth of photodetectors on the LISA spacecraft. We also demonstrated automatic phase locking between two lasers equipped with the same reference system. Our system and algorithm are simple enough to be implemented into spacecraft and will add robustness for the LISA mission. This concept can be applied for other applications, where absolute frequency knowledge of a 1064 nm laser is required.

## 2. Experimental Setup

Our experimental configuration is shown in Fig. 1. The light source was a 1064 nm Nd:YAG nonplanar ring oscillator (NPRO) with maximum output power of ~200 mW. The light was coupled into a polarization-maintaining (PM) single-mode (SM) fiber, and converted into 532 nm by a fiber-coupled waveguide second harmonic generator based on periodically poled potassium titanyl phosphate (PP:KTP). The PP:KTP waveguide had a phase-matching temperature of about 50 °C, which is controlled by a heater within its package. We typically operated this device at 120 mW input power and obtained 2 mW output power at 532 nm. The output fiber is PM SM for 532 nm, and thus the remaining 1064 nm light is attenuated within the fiber. The 532 nm light was coupled out from a fiber collimator and passed through the glass iodine cell with 60 mm length and 8 mm diameter. The transmitted power and a fraction of the input power were monitored by photodetectors. The vapor pressure of the iodine cell was set to be undersaturated by using a starved cell with no solid iodine, and thus no cooling or temperature control of the cell was required. As shown in Fig. 2, the peak absorption of the P(83)33-0 (1109) line was 18%, while the saturated absorption at 15 °C would be ~40% with the same cell length. The laser frequency was scanned by a computer program through a thermal tuning terminal of the laser. The program normalized the absorption signal by dividing the transmitted light power by the input light power.

We adopted the following tuning sequence. (i) Line identification: the program scans the laser frequency over the available thermal tuning range of >30 GHz. (ii) Coarse tuning: the program identifies Doppler-broadened absorption peaks and tunes the laser to a center of a peak specified in the program. Doppler-broadened absorption peaks typically have 1 GHz (500 MHz) full width at half-maximum at 532 nm (1064 nm). Peak identification was done simply by monitoring peak heights of the Doppler-broadened lines. The eight large Doppler-broadened lines (from 1104 to 1111) [3] were easily identified within the tuning range of the commercial Nd:YAG laser. The mode-hop region was automatically rejected by the program by monitoring the excess light power at the reference photodetector. (iii) Fine-tuning: the program finely scans the laser frequency around the specified peak and measures the relationship between the control voltage and transmitted light power. Then the program brings the laser to a specified side and height of the peak using a simple controller, and it keeps the laser frequency within a small range around the specified point. As an example, we used the intensity half-maximum of the Doppler-broadened absorption peak for simplicity and for its relatively high sensitivity to frequency change.

We set up two identical systems in order to demonstrate the use of the frequency reference for phase locking of the two lasers. Part of the light was picked off from each laser and interfered in a PM 50/50 fused

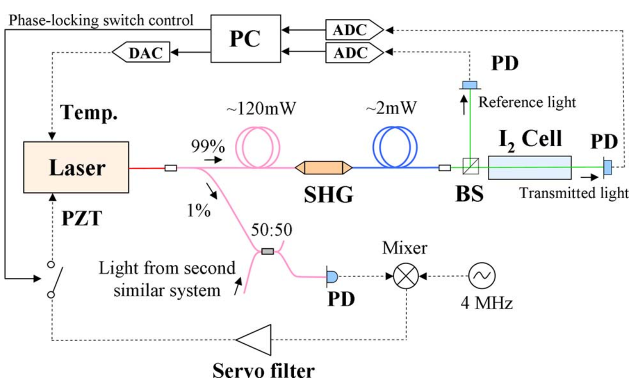


Fig. 1. (Color online) Schematic diagram of the iodine reference and automatic phase-locking system: SHG, waveguided second harmonics generator; BS, beam splitter; PD, photodetector; ADC, analog-to-digital converter; PC, personal computer with tuning program; DAC, digital-to-analog converter; and PZT, piezoelectric transducer.

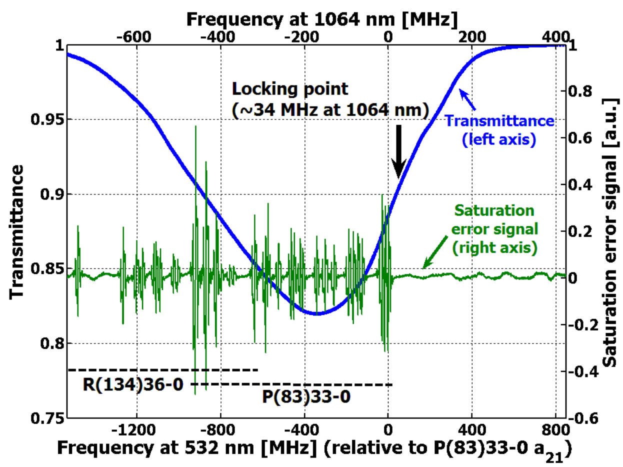


Fig. 2. (Color online) Doppler-broadened line of the undersaturated iodine cell and corresponding saturation error signal measured by the independent reference system. The target point was rising half-maximum of the peak, which is ~34 MHz higher than a half-frequency of P(83)33-0 $a_{21}$ hyperfine transition line.

fiber coupler. The resultant signal was fed back to one of the lasers after detection and demodulation for phase locking. The reference frequency for the demodulation mixer, namely, the offset frequency of the phase locking, was set to 4 MHz. The switch to activate the phase-locking servo was automatically controlled by the computer.

The absolute accuracy of one of the systems was evaluated by beating its laser against an independent reference laser, whose doubled frequency was locked to a hyperfine transition line [P(83)33-0 $a_{21}$ line at 563244541.4 MHz] by the saturation spectroscopy technique [4]. The location of the hyperfine line is shown in Fig. 2. Our saturation spectroscopy system is estimated to have $< \sim 1$ MHz absolute accuracy. Details of the system can be found in [5].

## 3. Experimental Results

### A. Absolute Frequency Accuracy of the Reference

Figure 3A shows the repeatability of the tuning process in terms of the beatnote frequency between the tuned laser and the reference laser locked to the P (83)33-0 $a_{21}$ line. Starting at any frequency inside the $>30$ GHz laser tuning bandwidth, the laser can be tuned to a specific frequency within 3 MHz uncertainty. Figure 3B shows the beatnote between two lasers independently tuned by the same algorithm. The beatnote frequency was always below 5 MHz, even without any electrical or optical link between the two systems. Thus, we estimated that the system has at least $\sim$10 MHz accuracy as a frequency reference.

### B. Phase-Lock Acquisition Between Two Independently Tuned Lasers

An example of phase-lock acquisition between two independently tuned lasers is shown in Figs. 4A and 4B. At first (time = 0 s), the two laser frequencies differed by over 6 GHz. After we sent a command to start the coarse tuning, the beatnote frequency was driven to $<50$ MHz within 30 s (Fig. 4A). After a secondary sweep around the target absorption line, the fine-tuning was engaged and the frequency difference dropped below 10 MHz within 50 s (Fig. 4B). When the lasers passed through the reference frequency (4 MHz), phase locking between the two lasers was automatically acquired (at time = 160 s).

## 4. Discussion

The frequency reference repeatability was mainly limited by the transmitted power fluctuation of typically $\sim$1%, which corresponds to the $\sim$10 MHz accuracy in the fine-tuning stage. A large time constant ($\sim$10 s) and nonlinearity in the thermal frequency tuning terminal limited the speed of the reference in the line identification and the coarse tuning stage. Improved software with a better algorithm could tune the lasers much more quickly to the target frequency. The use of a laser different than the NPRO (e.g., current tuning in diode laser) could give us much faster wavelength identification and lock acquisition. In our setup, $\sim$10 mV output voltage change in the photodetector corresponded to the 10 MHz accuracy. This requirement is not stringent, and, thus, ordinary photodetectors and 16 bit ADC/DAC can be used as the electronics.

This system can be adapted for space application in a straightforward way. A KTP frequency-doubling crystal has been already flown in the CALIPSO mission [6]. Periodically poled lithium niobate can also be used as a doubling device, and its radiation hardness has been already tested [5]. A glass cell (similar to our glass iodine cell) has been used for atomic rubidium clocks in global positioning system satellites [7] and has proven robust for space flight. The undersaturated iodine cell is insensitive to temperature change: as long as the cell temperature is higher than the saturation point, iodine pressure and, thus, the Doppler-broadened line shape could be calibrated by a small modification to our frequency tuning algorithm. The required laser power to obtain the $\sim$10 MHz accuracy was as low as 4 mW at 1064 nm (1.6 $\mu$W at 532 nm) in our test setup. Thus, only a

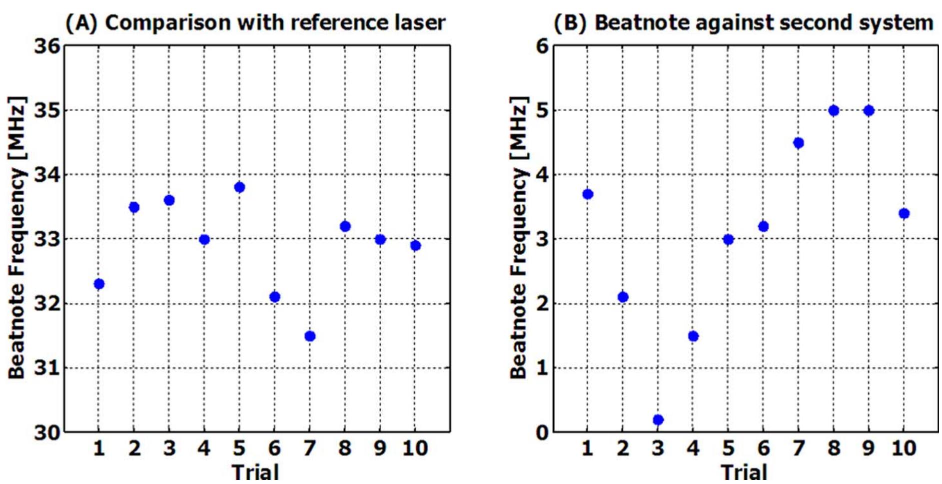


Fig. 3. (Color online) (A) Beatnote frequency between the reference laser and the laser tuned by going to iodine peak half-maximum. (B) Beatnote frequency between two iodine systems. These two measurements were done at the same time.

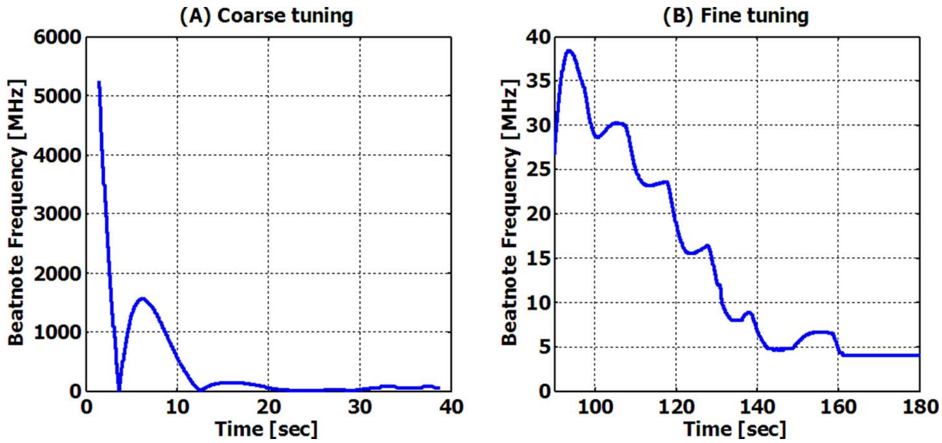


Fig. 4. (Color online) Beatnote frequency between two independently tuned lasers, in the (A) coarse tuning step and (B) fine-tuning step. The horizontal axis represents the time after the tuning command was sent. In the fine-tuning step, the phase-locking servo was turned on. Phase locking with a 4 MHz offset was automatically acquired at the time of 160 s.

small fraction of laser output (2 W level in LISA) is needed for the reference. Finally, the alignment stability of glass cell and other free-space optical components is not critical, because photodetectors with a large area can be used for the slow intensity monitoring.

It should be noted that the frequency reference provides a monitor of the laser tuning range, tuning efficiency, and possibly mode hopping as well as absolute frequency knowledge. It will significantly reduce technical risks associated with LISA constellation acquisition [8]. This simple reference may be useful for other lidar missions, in which Nd:YAG is used as a master laser, in order to monitor the lasing status and frequency. Although our system works as a reference only at the absorption peaks of iodine, the range (~500 MHz × 8) is wide enough for most applications.

## 5. Summary

We demonstrated the use of a simple iodine reference for frequency monitoring and automatic phase locking with 4 MHz frequency offset between two independently tuned lasers. The reference system is very simple and can be easily adapted for space use; it has no frequency or intensity modulators and no iodine cell cooler. Its absolute frequency accuracy was 10 MHz and repeatability was ~3 MHz. This simple frequency reference will allow deterministic lock acquisition between distant lasers in the LISA spacecraft constellation using photodetectors with a 20 MHz bandwidth. The iodine reference system can also reduce risks of other space interferometry missions by providing an independent diagnostic tool of lasers.

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